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Design and Analysis of Regeneration from Turbocharger

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Abstract: A significant portion of fuel energy in internal combustion engines is lost through exhaust gases. This study presents the design and analysis of a turbocharger-based energy recovery system that converts waste exhaust energy into electrical power. An axial flux permanent magnet generator (AFPMG) is integrated with the turbocharger shaft to harness high-speed rotational energy. Due to the extremely high turbine speed (~120,000 rpm), a speed reduction mechanism is employed to maintain generator operation within safe limits (20,000–40,000 rpm). The system is modelled and analysed using ANSYS Workbench and ANSYS Electronics Maxwell. Key parameters such as magnetic flux distribution, induced voltage, and efficiency are evaluated. Results indicate that the system can generate approximately 4–5 kW of electrical power under normal operating conditions. The generated AC power is rectified and stored for vehicle applications, improving overall engine efficiency and reducing fuel consumption
Keywords: Turbocharger energy recovery, Axial Flux Permanent Magnet Generator (AFPMG), High-speed generator, ANSYS Workbench, ANSYS Maxwell, Hybrid turbocharger system.

I. INTRODUCTION

The rapid growth of the automobile industry has increased the demand for energy-efficient vehicles. Conventional internal combustion engines waste a significant portion of fuel energy in the form of exhaust gases and heat. Studies show that nearly 30–40% of fuel energy is lost through exhaust gases. Recovering this wasted energy can significantly improve vehicle efficiency. A turbocharger is widely used in modern engines to increase power output by utilizing exhaust gas energy. The turbine side of the turbocharger rotates at extremely high speeds, typically between 80,000 rpm and 150,000 rpm, depending on the engine size and operating conditions. Although the turbocharger utilizes exhaust energy to compress intake air, some of the mechanical energy from the turbine shaft can still be recovered. This recovered energy can be converted into electrical power using a generator connected to the turbocharger shaft. In this project, an axial flux permanent magnet generator (AFPMG) is integrated with the turbocharger shaft to convert mechanical energy into electrical energy. The generated electricity can be stored in a battery and used later to power electrical components of the vehicle. The generator operates at a reduced speed compared to the turbocharger using a mechanical reduction mechanism. This prevents excessive mechanical stress on the generator components.

II. METHODOLOGY

The methodology of this project focuses on the design and analysis of a turbocharger-based electrical energy recovery system using an axial flux permanent magnet generator. The project follows a systematic approach that includes system study, generator design, simulation, and performance evaluation.

A. *Turbocharger System Analysis*

The turbocharger system is first analysed to understand its energy potential. Exhaust gases drive the turbine at speeds up to 120,000 rpm, generating approximately 14 kW of mechanical power. This high-speed rotational energy is utilized as a source for electrical energy recovery.

B. *Conceptual Design of Energy Recovery System*

A generator is integrated with the turbocharger shaft to convert mechanical energy into electrical energy. To ensure mechanical stability at high speeds, a speed reduction mechanism is incorporated, limiting the generator operating range to 10,000–20,000 rpm.

C. *Selection of Generator*

An axial flux permanent magnet generator (AFPMG) is selected due to its high-power density, compact design, and efficiency. The generator features a double-rotor configuration with N48 neodymium permanent magnets.

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D. *Generator Design Parameters*

Key parameters such as number of poles, air gap length, magnet thickness, stator dimensions, and rotor diameter are optimized to achieve an output power of 4–5 kW.

E. *Simulation and Analysis*

Finite element analysis is conducted using ANSYS Maxwell. A detailed model is developed to evaluate magnetic flux distribution and induced voltage.

III. SOFTWARE USED FOR ANALYSIS

The simulation and analysis of the proposed system were carried out using ANSYS Workbench, ANSYS Electronics Desktop, and ANSYS Maxwell. ANSYS Workbench served as an integrated platform for geometry handling, structural evaluation, and thermal analysis. It enabled efficient integration of the turbocharger and generator models, while also supporting parametric studies to optimize key design variables such as rotor diameter, air gap, and magnet thickness. Structural analysis was performed to assess the mechanical stresses acting on the rotor and shaft at high rotational speeds, while thermal analysis provided insight into heat generation and distribution within critical components such as stator windings and permanent magnets. For electromagnetic analysis, ANSYS Electronics Desktop was employed, with ANSYS Maxwell used for detailed finite element simulations. The generator model was directly developed and analysed in Maxwell to evaluate magnetic flux distribution, induced voltage in the stator windings, and electromagnetic torque generation. In addition, core losses, eddy current losses, and overall efficiency were studied to assess the generator's performance under operating conditions. The use of these advanced simulation tools enabled comprehensive validation of both mechanical and electromagnetic characteristics prior to prototype development, thereby reducing design uncertainties and enhancing system reliability.

IV. DESIGNING OF TURBO AND AFMP GENERATOR

The complete design mainly consists of the following subsystems:

- Turbine Blade
- Volute Casing
- Permanent Magnet for Axial Flux Machine
- Permanent Magnet and Generator Design

A. *Turbine Blade Design*

The turbine blade plays a crucial role in extracting energy from exhaust gases and converting it into rotational motion. In this project, the blade was designed to operate under high temperature, pressure, and rotational speed conditions by considering key parameters such as exhaust gas velocity, blade angle, curvature, and speed. An efficient blade profile was selected to minimize flow separation and turbulence, thereby improving aerodynamic performance and energy conversion efficiency. The design process was carried out using ANSYS Vista RTD, which generated optimized turbine models based on input conditions, and the final blade geometry was developed using ANSYS BladeGen.

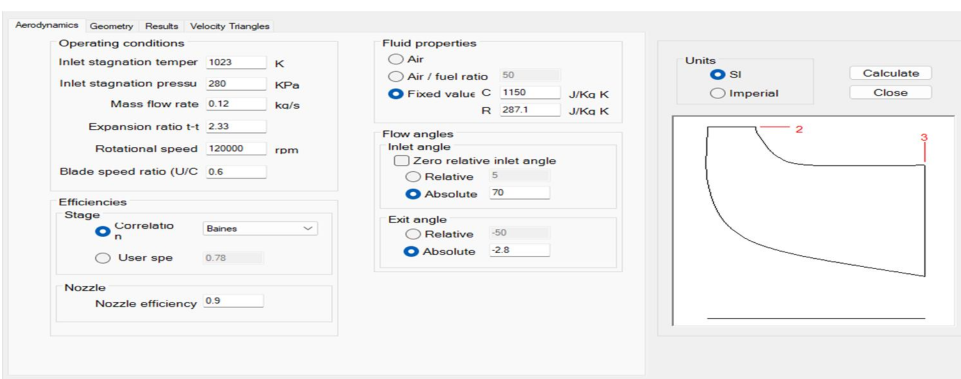

Fig. 1 Input Parameters of Turbine Blade

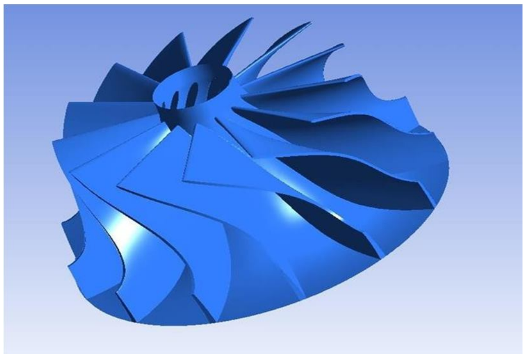

Fig. 2 Generated Blade in SolidWorks

The blade material must also be capable of operating under severe thermal stresses. Therefore, materials with high temperature resistance and good fatigue strength are preferred for turbine blade construction.

B. Volute Design

The volute is the spiral-shaped casing that directs exhaust gases uniformly toward the turbine wheel. The volute design plays a major role in distributing the exhaust flow evenly and maintaining pressure energy before it enters the turbine blades.

In this project, the volute was designed with the aim of:

- Ensuring smooth flow of exhaust gases
- Minimizing pressure losses
- Improving turbine inlet distribution
- Increasing energy transfer to the turbine wheel

The cross-sectional area of the volute gradually changes along the spiral path so that the exhaust gas reaches the turbine blades at the desired velocity and pressure. A properly designed volute improves turbine efficiency and reduces flow imbalance.

a) Volute Design Calculation

$\dot{m} = 0.12 \ kg/s$

$P = 2.8 \ bar = 280000 \ Pa$

$T = 1023 \ K$

$R = 287 \ J/kg \cdot K$

$\gamma = 1.33$

$M = 0.46$

$$a = \sqrt{\gamma RT} = \sqrt{1.33 \times 287 \times 1023} \approx 625 \ m/s$$

$$V = M \cdot a = 0.46 \times 625$$

$$V = 287.5 \ m/s$$

$$A = \frac{\dot{m} R T}{P V}$$

$$A = \frac{0.12 \times 287 \times 1023}{280000 \times 287.5}$$

$$A_{360} = 437 \ mm^2$$

$$A(\theta) = A_{360} \times \frac{\theta}{360}$$

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Table 1 Volute Area in Certain Angles

Angle(degree)	Area (mm^2)
90	109
180	219
270	328
360	437

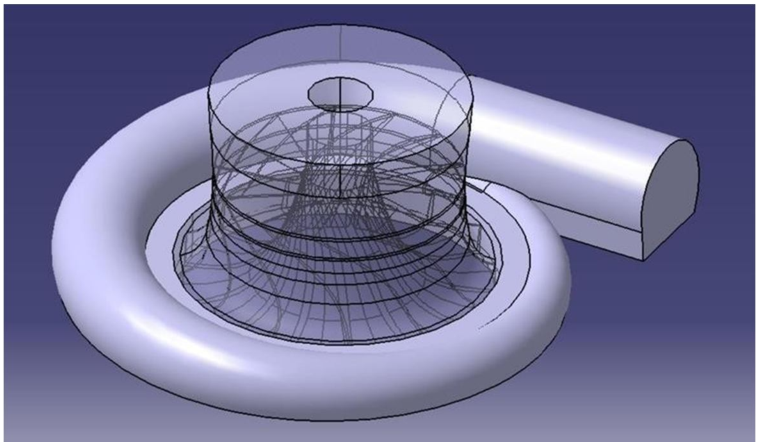

Fig. 3 Designed Volute in 3D

Special attention was given to the inlet geometry and scroll shape to obtain effective exhaust gas guidance. The volute design also supports compactness and easy integration with the turbine housing.

After completing the model editing and assigning the material to all parts included in model, now we have to do the most important part of the analysis that is meshing. Meshing the model will divide the large component into small elements and nodes, which will make the component easy and convenient to perform the analysis.

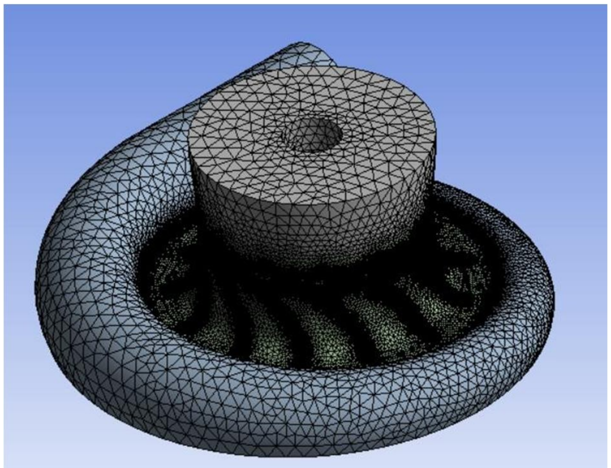

Fig. 4 Meshing of Turbo

C. Permanent Magnet Axial Flux Machine

NdFeB – N48H magnet was selected for this project because it provides a strong magnetic field, compact size, and high efficiency. Compared to other magnets, it gives better performance and is suitable for the project requirement. Hence, NdFeB – N48H is used due to its high magnetic strength and reliable operation.

Fig. 5 Neodymium Permanent Magnets

D. Permanent Magnet and Generator Design

A permanent magnet is used in this project as part of the electrical machine integrated with the turbocharger. Permanent magnets provide the magnetic field without requiring external excitation, which reduces power loss and improves efficiency.

The use of permanent magnets offers the following advantages:

- High power density
- Compact size
- Reduced electrical losses
- Improved efficiency
- Fast dynamic response

Table 2 Parameters of Axial Flux Permanent Magnet Generator

Parameters	Values
Outer Stator Diameter/Outer Rotor Diameter	160mm
Inner Stator Diameter/Inner Rotor Diameter	72mm
Mean Diameter	116mm
Axial Length	50mm
Air Gap Length	1mm
Rotor Type	Disc Type
Number of Slot	12
Number of Poles	10
Magnet Thickness	6mm
Turns per Coil	9
Number of Strands	12

The permanent magnet is placed in the rotor section of the axial flux machine. It creates a constant magnetic field which interacts with the stator windings to generate torque or electrical power, depending on the mode of operation.

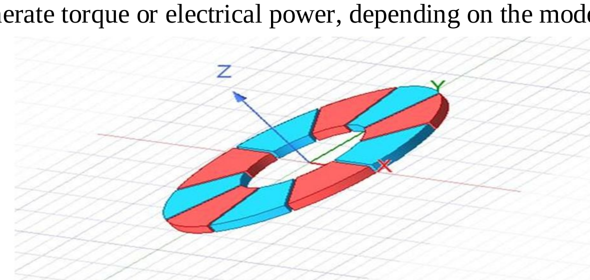

Fig. 6 Designed Magnets

The selection of permanent magnet material is important because it affects magnetic strength, thermal stability, and durability. High-performance magnetic materials are generally preferred for such applications to ensure stable operation at high speed.

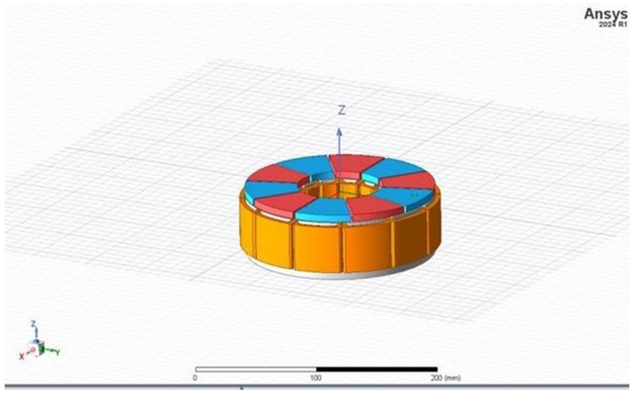

Fig. 7 Axial Flux Permanent Magnet Generator

The axial flux permanent magnet machine is integrated with the turbocharger shaft system. It can assist the rotor during low exhaust energy conditions, thereby reducing turbo lag. It may also work as a generator during excess exhaust energy conditions, depending on the system design. Because of its disc-type geometry, the axial flux machine is suitable for compact turbocharger layouts where space and efficiency are important.

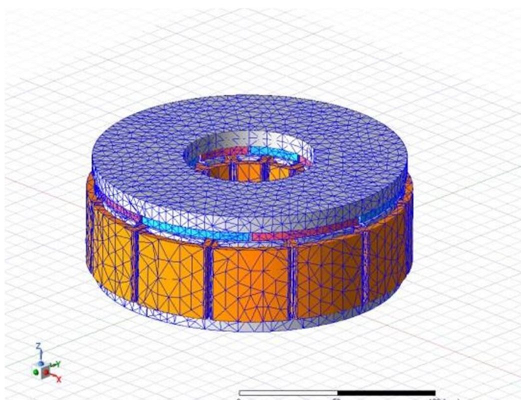

Fig. 8 Meshing of AFPMG

The meshing operation of the designed model was carried out in ANSYS Electronics to prepare it for accurate numerical analysis. A fine triangular surface mesh was generated over the entire geometry, with higher mesh density applied in critical regions such as edges, interfaces, and areas with expected high field variation. This ensures better resolution of electromagnetic behavior and improves the accuracy of the simulation results. The mesh quality was carefully controlled to maintain an optimal balance between computational efficiency and solution precision. The resulting discretized model enables reliable evaluation of the system's performance under operating conditions.

V. RESULT AND DISCUSSION

The performance of the proposed turbocharger system was analyzed using two different simulation platforms. The aerodynamic and flow behavior of the turbine and volute were studied using Computational Fluid Dynamics (CFD) in ANSYS, while the electrical performance of the integrated axial flux permanent magnet machine was evaluated using ANSYS Electronics Maxwell. The combined analysis helped in understanding both the fluid dynamic behavior and the electrical energy generation capability of the designed system. The CFD simulation was carried out to study the flow of exhaust gas through the volute and turbine blade section of the turbocharger. The objective of this analysis was to examine pressure distribution, velocity variation, and flow characteristics within the designed geometry.

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A. Pressure Distribution

The CFD results showed that the pressure was maximum at the volute inlet and gradually decreased toward the turbine blade exit. This pressure drop indicates that the exhaust gas energy was effectively utilized to rotate the turbine wheel. A smooth pressure variation through the volute confirms that the volute geometry was able to guide the flow properly toward the turbine blades.

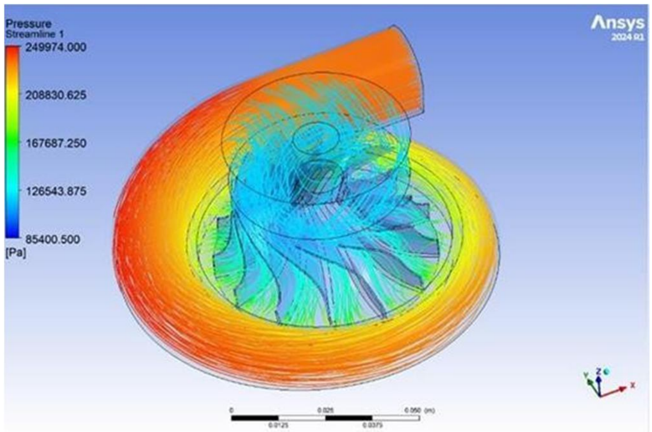

Fig. 9 Pressure Streamline

The figure represents a fluid flow simulation result obtained using ANSYS, showing the pressure distribution and streamline pattern within the modeled geometry. The pressure contour ranges from a minimum of 85,400.5 Pa (blue region) to a maximum of 249,974 Pa (red region). Intermediate pressure levels include 126,543.875 Pa, 167,687.25 Pa, and 208,830.625 Pa indicating a gradual pressure variation throughout the flow domain. The colored contours illustrate that high-pressure regions are concentrated at the outer curved section, while lower pressure zones are observed near the central region. The streamlines depict the flow path of the fluid, showing swirling and rotational motion as the fluid moves inward, which suggests the presence of vortices and complex flow behavior. This analysis is important for identifying pressure losses, flow separation, and efficiency of the system, thereby aiding in design optimization and performance improvement.

B. Pressure Contour

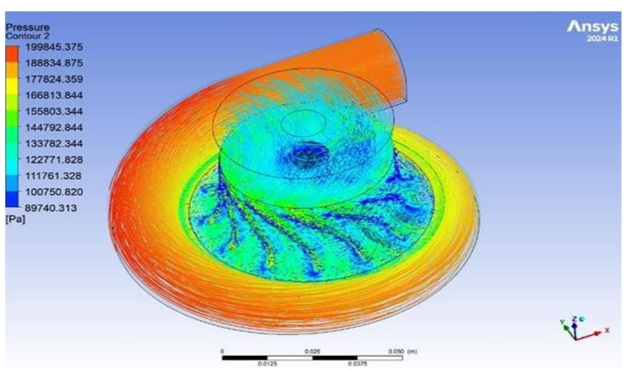

Fig.10 Pressure Contour

The figure represents a pressure contour simulation obtained using ANSYS, illustrating the pressure distribution within the modeled system along with the internal flow behavior. The pressure varies from a minimum of 89,740.313 Pa (dark blue region) to a maximum of 199,845.375 Pa (red region), with intermediate values of 100,750.820 Pa, 111,761.328 Pa, 122,771.828 Pa, 133,782.344Pa, 144,792.844Pa, 155,803.344Pa, 166,813.844 Pa,177,824.359 Pa, and 188,834.875 Pa, indicating a smooth gradient across the domain. The high-pressure region is observed along the outer curved passage, while lower pressure zones are concentrated near the central region and blade passages. The distribution shows how the fluid loses pressure as it moves inward, highlighting energy transfer and flow acceleration effects. The contour also reveals non-uniform pressure patterns across the blades, suggesting complex flow interactions such as turbulence and secondary flows. This analysis is essential for evaluating pressure drop, flow efficiency, and overall performance, helping in optimizing the design for improved fluid dynamic behavior.

C. Velocity Distribution

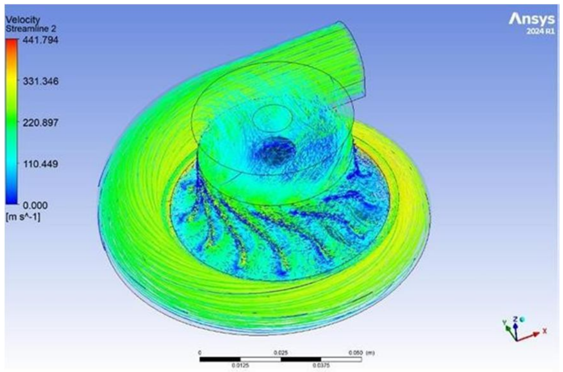

Fig. 11 Velocity Streamline

The figure shows a velocity streamline analysis performed using ANSYS, illustrating the flow pattern and speed distribution within the system. The velocity ranges from 0 m/s to 441.794 m/s, with higher velocities along the outer curved region and lower velocities near the center due to flow resistance and recirculation. The streamlines indicate swirling flow and vortex formation, which are important for understanding flow behavior, energy transfer, and overall system efficiency.

D. Temperature Distribution

The temperature behavior of the turbocharger was analyzed to study the thermal changes occurring in the turbine and compressor sections during operation. It was observed that the turbine side experiences a higher temperature due to the hot exhaust gases entering the system, while the compressor side shows a comparatively lower temperature. The temperature distribution indicates that heat transfer takes place through the turbocharger housing and rotating components. As the exhaust gas temperature increases, the turbine speed also increases, which improves the compression process. However, excessive temperature may lead to thermal stress, material degradation, and reduction in overall efficiency. Therefore, temperature behavior is an important factor in evaluating the performance and durability of the turbocharger.

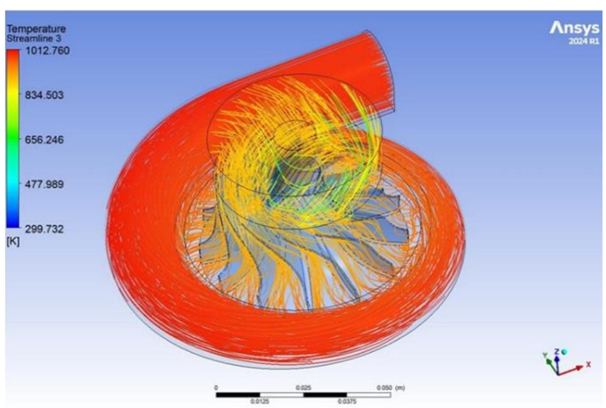

Fig. 12 Temperature Streamline

The figure shows a temperature streamline analysis using ANSYS, illustrating heat distribution in the system. The temperature ranges from 299.732 K to 1012.760 K, with higher temperatures at the outer region and lower near the center. The streamlines indicate heat flow with a swirling pattern, helping to analyze heat transfer and identify hot spots.

E. Torque Produced

The analysis is done in steady state using pressure based coupled solver as it can solve compressible flows.RNG k-epsilon model is used to solve the turbulence. Fluid used is flue gas with density modelled as ideal gas. Multiple Rotating Frame (MRF)model is used to model the rotating turbine with domain containing the turbine rotating at 120000 RPM.For inlet Mass flow inlet boundary condition is used with a mass flow rate if 0.12 kg/s and temperature of 1023k.

Outlet is modelled as pressure outlet with 120 Kpa pressure. Blade is given rotating boundary condition of 120000 RPM.All residuals are given a target of 0.001 for continuity, momentum and turbulence equations while 0.000001 for energy. Torque on the turbine was also monitored reaching a stable value of 1.11n-m.

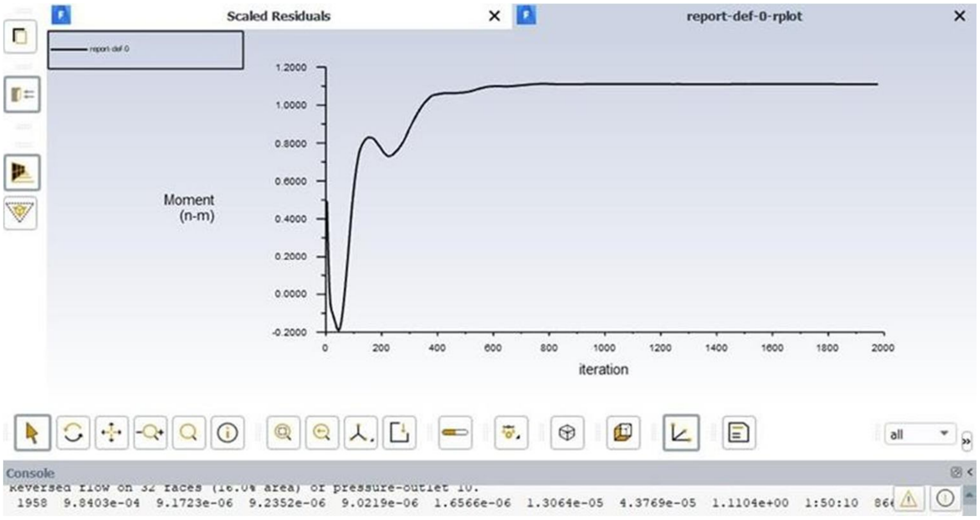

Fig. 13 Result of Torque Produced

The graph shows the regenerative torque of the turbocharger over iterations. After initial fluctuations, the torque stabilizes at about 1.11 n-m, indicating steady-state operation and efficient energy recovery. By using power equation P=2πNT/60 we have found that power is 14 kw.

$$P = \frac{2\pi \times N \times T}{60}$$

$$P = \frac{2\pi \times 12000 \times 1.11}{60} = 14kW$$

F. Magnetic Flux Density Distribution

The electrical energy generation capability of the system was analyzed using ANSYS Electronics Maxwell. The axial flux permanent magnet machine integrated into the turbocharger was simulated to study the magnetic flux distribution, induced voltage, and electricity generation performance.

The Maxwell simulation showed that the magnetic flux was well distributed across the air gap and stator region of the axial flux machine. The use of permanent magnets provided a stable magnetic field, which is essential for efficient electromagnetic induction.

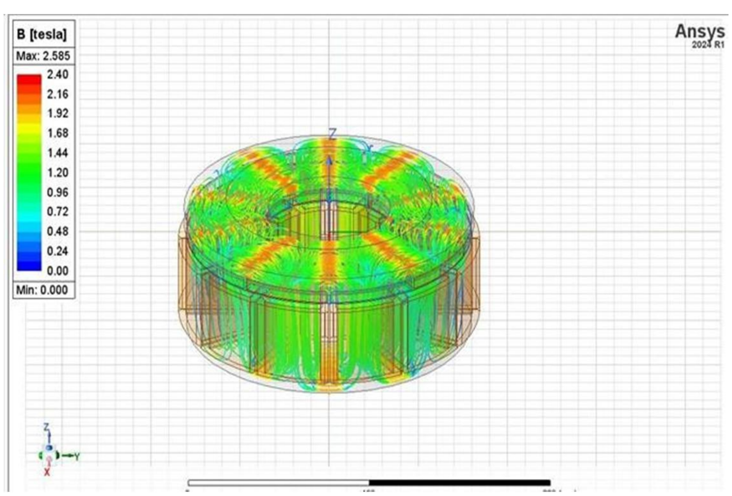

Fig. 14 Magnetic Flux Streamline in Coils

The figure shows magnetic flux density distribution in coils using ANSYS Electronics Maxwell, ranging from 0 T to 2.585 T. High flux is observed in the core regions, while low flux appears in the air gap. It illustrates flux paths and helps identify saturation and performance of the design. The flux pattern confirmed that the axial flux arrangement was effective for compact design and proper magnetic coupling between rotor and stator.

G. Magnetic Loading

The magnetic loading, indicated by the flux density, ranges from 0.147 T to 1.450 T, showing effective utilization of the magnetic circuit. The machine uses 10 pole magnets, where the magnetic flux is arranged such that, it follows an ascending order in the north pole region and descending order in the south pole region, ensuring a balanced and continuous flux distribution. High flux regions approach saturation, improving performance but increasing loss risk, while the air-gap flux remains fairly uniform for smooth operation. Overall, the design is efficient, with slight scope for reducing saturation and leakage effects.

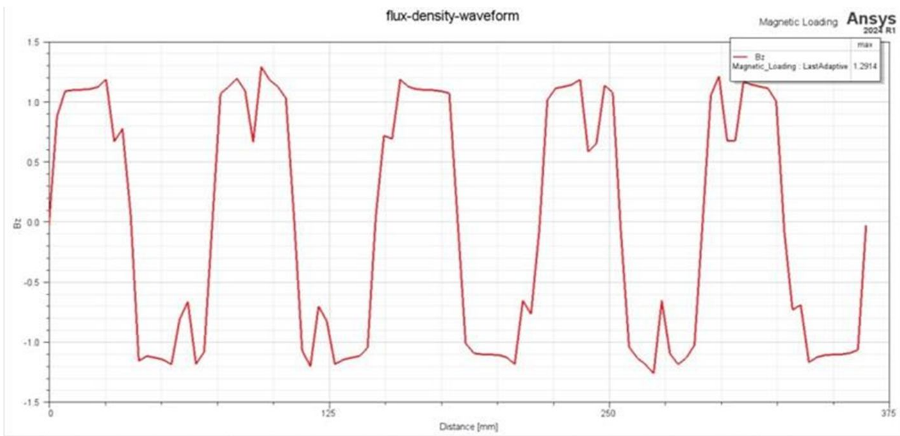

Fig. 15 Each Magnet Flux Loading

H. Induced Voltage Generation (No Load Condition)

Fig. 16 Induce Voltage in Each Phase (No Load Condition)

The graph shows the induced voltage under no-load condition. The voltage waveforms are balanced and sinusoidal with higher magnitude (around 186 V) compared to load condition, as there are no voltage drops due to internal resistances, indicating ideal generator operation.At 12000 rpm under no-load condition, the generator produces an RMS phase voltage of 186 V. Assuming a load resistance of 10 Ω, the phase current is calculated as;

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$$Iph = \frac{Vph}{R} = \frac{186}{10} = 18.6\ A$$

For a star-connected system, the line voltage is;

$$Vli = \sqrt{3} \times Vph = \sqrt{3} \times 186 = 322\ V$$

The output power is then given by

$$P = \sqrt{3} \times Vli \times Ili \times cos\phi$$
$$= \sqrt{3} \times 322 \times 18.6 \times 0.9 = 9.3\ kW$$

Where Vli is the line voltage, Ili is the line current, and cosϕ = 0.9 is the power factor considering mechanical gear reduction.

I. *Induced Voltage Generation (Load Condition)*

The rotation of the turbocharger shaft caused the rotor magnets to move relative to the stator windings, thereby inducing voltage. The simulation results indicated that the machine was able to generate electrical output when the rotor rotated at the designed speed.

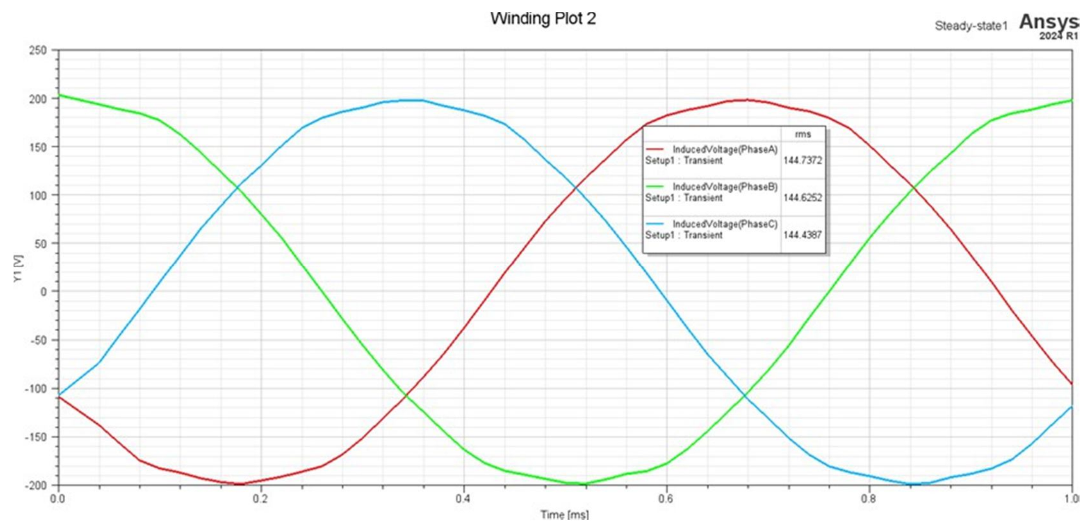

Fig.17 Induce Voltage in Each Phase (Load Condition)

The graph shows induced voltage under load. Due to phase and coil resistance, there is a slight voltage drop, but all phases remain balanced at 144 rms Voltage, indicating stable operation. At 12000 rpm under no-load condition, the generator produces an RMS phase voltage of 144 V.

Assuming a load resistance of 10 Ω, the phase current is calculated as;

$$Iph = \frac{Vph}{R} = \frac{144}{10} = 14.4\ A$$

For a star-connected system, the line voltage is;

$Vli = \sqrt{3} \times Vph = \sqrt{3} \times 144 = 249\ V$

The output power is then given by

$P = \sqrt{3} \times Vli \times Ili \times cos\phi = \sqrt{3} \times 249 \times 14.4 \times 0.9 = 5.6\ kW$

Where Vli is the line voltage, Ili is the line current, and cosϕ = 0.9 is the power factor considering mechanical gear reduction.

J. *Combined Performance Discussion*

The combined results from ANSYS CFD and ANSYS Electronics Maxwell clearly demonstrate that the proposed turbocharger system performs effectively in both aerodynamic and electrical aspects. The CFD analysis confirms that the volute enables smooth exhaust gas flow, while the turbine blades efficiently extract energy, with the observed pressure drop and velocity increase supporting effective turbine rotation. From the electromagnetic analysis, it is evident that the axial flux permanent magnet configuration produces strong magnetic flux linkage, successfully inducing electrical voltage and indicating the system's capability to recover a portion of otherwise wasted exhaust energy.

Overall, the project successfully validates the concept of integrating turbocharging with electrical energy generation, where the mechanical energy derived from exhaust gases is converted into turbine shaft rotation and further utilized by the axial flux permanent magnet generator to produce electricity.

The obtained results are significant as they demonstrate that the designed system can effectively serve a dual purpose: enhancing engine performance through turbocharging while simultaneously generating electrical energy using an integrated electromagnetic system. This dual functionality makes the system highly suitable for advanced automotive applications where improving energy efficiency and recovering waste energy are critical. Furthermore, the integration of aerodynamic and electromagnetic design elements enhances the overall utility and effectiveness of the turbocharger system, making it a promising solution for modern energy-conscious engineering applications.

VI. CONCLUSIONS

This paper demonstrates the feasibility of recovering waste energy from a turbocharger using an axial flux permanent magnet generator (AFPMG). The high-speed turbocharger shaft, operating at approximately 120,000 rpm, provides a viable source of mechanical energy, which is effectively converted into electrical energy through a speed reduction mechanism and optimized generator design. Simulation using ANSYS Workbench and ANSYS Maxwell confirms that the system can generate approximately 4–5 kW of electrical power under normal operating conditions. The results also indicate that increased current leads to higher temperature due to resistive losses, which in turn affects material resistance and overall system performance. The recovered electrical energy can be utilized for auxiliary loads and battery charging, thereby improving overall engine efficiency and reducing fuel consumption. Hence, the proposed system offers a promising solution for energy recovery in automotive applications.

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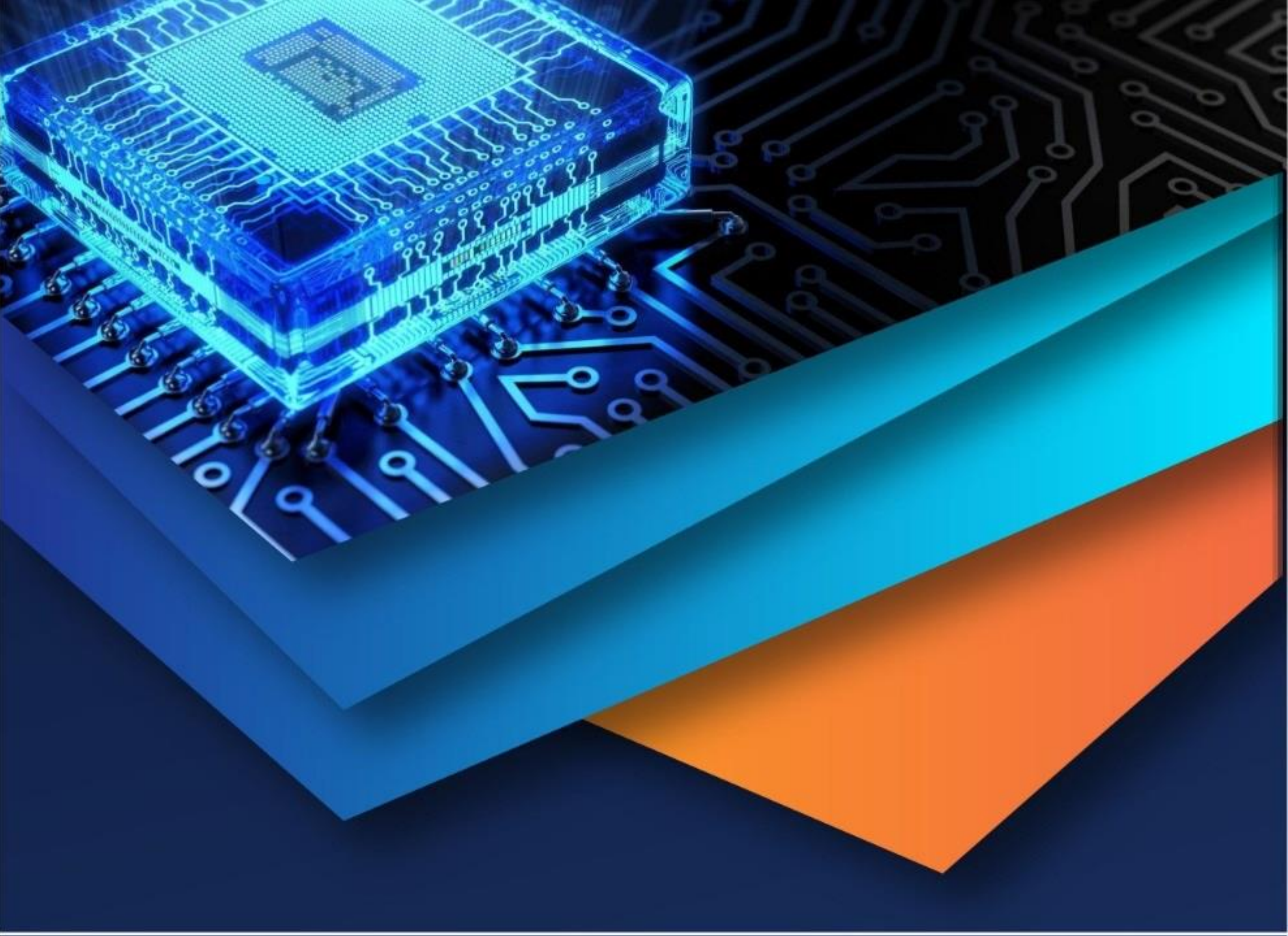

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